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The research covered by this report was aimed at developing a broad, optimization-based methodology for use in computer-aided-design of engineering systems. To this end, research was carried out in the following areas: (i) the development of a theory which can be used as a general guide in the construction of semi-infinite optimization, shape optimization and optimal control algorithms; (ii) the development of various new semi-infinite optimization and optimal control algorithms; (iii) the development of techniques for formulating system stability and worst-case requirements as well-conditioned semi-infinite inequalities; (iv) the exploration of the use of optimization in the design of control systems; and finally, (v) interactive software for optimization-based control system design. (KR)

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NUMERICAL OPTIMIZATION, SYSTEM THEORETIC AND SOFTWARE TOOLS FOR THE INTEGRATED DESIGN OF FLEXIBLE STRUCTURES AND THEIR CONTROL SYSTEMS

Final Technical Report
AFOSR Grant 86-0116
(September 30, 1986 — September 29, 1989)

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Grant No.: AFOSR-86-0116

FINAL REPORT

September 30, 1986 to September 29, 1989.

ABSTRACT

The research covered by this report was aimed at developing a broad, optimization-based methodology for use in computer-aided-design of engineering systems. To this end, research was carried out in the following areas: (i) the development of a theory which can be used as a general guide in the construction of semi-infinite optimization, shape optimization and optimal control algorithms; (ii) the development of various new semi-infinite optimization and optimal control algorithms (iii) the development of techniques for formulating system stability and worst-case requirements as well-conditioned semi-infinite inequalities; (iv) the exploration of the use of optimization in the design of control systems; and finally, (v) interactive software for optimization-based control system design.

Five doctoral dissertations were completed during this period [14, 15, 20, 41, 42].

FINAL REPORT

Our accomplishments over the three year period of September 30, 1986 to September 29, 1989 can be organized as follows:

(a) Nonsmooth Optimization Algorithm Theory

In [7], which is a 70 page paper, we have presented our view of the mathematical foundations of nondifferentiable optimization in engineering design. The theory presented in [7] not only helps to understand existing nondifferentiable optimization algorithms, but it also provides guidelines for the development of new ones. In particular, the theory in [7] points out the possibility of the construction of self scaling algorithms.

(b) Self Scaling Minimax Algorithms

When linear multivariable feedback-system controllers are affinely parametrized, as is commonly done in H^∞ design, the resulting optimal design problems are convex. However, the affine parametrization can also introduce severe ill-conditioning. To determine what effect domain transformations might have on minimax algorithm performance, we undertook a couple of studies of the effects of transformations on rate of convergence, [13, 21, 22]. We showed that an adaptively constructed domain transformation technique results in much improved minimax algorithms.

(c) Consistent Discretization Techniques for Semi-infinite Optimization and Optimal Control

Since discretization cannot be avoided in the solution of semi-infinite optimization and optimal control problems, we have developed in [27, 36, 39, 40] several discretizations strategies which are consistent with convergence and fast solution of semi-infinite optimization and optimal control problems. These are to be used in the solution of control system design problems in which one shapes various closed-loop responses as well as in solution of optimal control problems with ODE as well as with PDE dynamics.

(d) Semi-infinite Optimization Algorithms for Problems with Exclusion Constraints

Exclusion constraints occur in floor planning and other layout problems as well as in robot path planning. In [3] we have developed an algorithm for the solution of optimization problems with *exclusion* constraints, which are combinatoric in nature and which arise integrated-circuit macro-cell placement problems, as a result of nonoverlap requirements. We have developed a particularly efficient formulation of the problem of placement of macro-cells in [16], in the form of an optimization problem with exclusion constraints, and have carried out computational experiments to test it.

(e) Extension of Newton's Method to Semi-infinite Minimax Problems

In [9] we have presented an efficient generalization of Newton's method for the minimization of the maximum of a finite number of functions. In [37], an ingenious, novel technique is used to develop a superlinearly converging version of Newton's method for semi-infinite minimax problems. The algorithm is shown to converge with root rate at least 3/2.

(f) Efficient Search Direction Computation Subprocedures

Search direction computations consume a considerable amount of time in the course of semi-infinite optimization of engineering designs. In [26] we have proposed a new, highly efficient method for this purpose.

(g) Unified Phase I - Phase II Algorithms

Current phase I - phase II constrained semi-infinite minimax algorithms exhibit a certain amount of undesirable discontinuity in the way they behave in the transition from the infeasible region to the feasible region. This is due to the fact that they switch step size rules in going across this boundary. In [32] we present a new unified phase I - phase II method of feasible directions for semi-infinite optimization. It has the unique property that in phase II it constructs iterates well away from the boundary of the feasible set, and as a result it is the only algorithm in its class for which there now exists a theoretically justified implementation; in fact, it was shown in [40] that this algorithm can be implemented with rate of convergence preservation.

(h) Barrier Function Methods

Prof. C. Gonzaga, one of our collaborators, has explored the possibility of improving Karmarkar's linear programming algorithm, in a preliminary stage to the development of interior penalty function algorithms for minimax problems.

In [28], the linear programming problem is transcribed into a non-linear programming problem in which Karmarkar's logarithmic potential function is minimized in the positive cone generated by the original feasible set. The resulting problem is then solved by a master algorithm that iteratively rescales the problem and calls an internal unconstrained non-linear programming algorithm. Several different procedures for the internal algorithm are proposed, giving priority either to the reduction of the potential function or of the actual cost. Karmarkar's algorithm is equivalent to the method in this paper in the special case when the internal algorithm is reduced to a single steepest descent iteration. All variants of the new algorithm have the same complexity as Karmarkar's method, but the amount of computation is reduced by the fact that only one projection matrix must be calculated for each call of the internal algorithm.

Reference [29] describes a short-step penalty function algorithm that solves linear programming problems in no more than $O(n^{0.5}L)$ iterations. The total number of arithmetic operations is bounded by $O(n^3L)$, carried on with the same precision as that in Karmarkar's algorithm. Each iteration updates a penalty multiplier and solves a Newton-Raphson iteration on the traditional logarithmic barrier function using approximated Hessian matrices. The resulting sequence follows the path of optimal solutions for the penalized functions as in a predictor-corrector homotopy algorithm.

More recently see [31, 38], we have found an interior penalty approach can also be used to construct highly effective semi-infinite minimax algorithms. These algorithms have been found to outperform other first order semi-infinite minimax algorithms, both in speed and in robustness; furthermore, they have a particularly simple structure which gives them great advantages in real time applications where algorithms are hard-coded.

(i) Algorithms for the Solution of Optimal Control Problems with State and Control Constraints, ODE/PDE Dynamics

In [5] we have presented an exact penalty function algorithm for the solution of optimal control problems with ordinary differential equation dynamics, state, and control constraints. In [20, 30, 39] this algorithm was extended to apply to problems with partial differential equation dynamics. Our new discretization theory was used to produce an implementable version of this algorithm and it was found the the new discretization techniques result in significantly more efficient efficient implementations than those produced using the earlier Klessig-Polak theory. The resulting algorithm was used in computational experiments in the optimal slewing of flexible structures, which were described in [17].

(j) Stability Tests and Loop-Shaping Requirement Specification

In [8] we have presented a new stability test for linear, time invariant multivariable feedback systems, in the form of a differentiable semi-infinite inequality, and have illustrated its use in the design of stabilizing compensators via semi-infinite optimization. In [23], we presented a version of this test which can be used in the design of *finite dimensional* controllers for infinite dimensional feedback-systems via semi-infinite optimization. The applicability of this test to systems with point actuators and sensors was extended in [33]. In [18] we presented a coherent approach to semi-infinite optimization-based design of both open-loop and closed-loop control systems for flexible structures. In particular, we showed that frequency domain design of closed loop systems, using our stability test, produces finite-dimensional controllers without spillover effects. In [24] we have shown that quite simple PID type finite dimensional controllers can be used to stabilize a class of feedback-controlled flexible structures.

(k) Design of Control Systems via Constrained Optimization in H^∞

In [11, 12] and [14], we have explored various aspects of the design of linear multivariable feedback-systems via constrained semi-infinite optimization in H^∞ spaces. These included a study of expansions of the controller in a series, development of expressions for both time- and frequency-domain loop shaping, as well as an exploration of the numerical properties of the ensuing *convex* optimal design problem.

(l) Novel Control Schemes and Computational Procedures

In [6] we have presented a novel adaptive control scheme for ARMA plants. The scheme is

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